Magneto-Optical Probing of Weak Disorder in a Two-Dimensional Hole Gas

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In two-beam magneto-photoluminescence spectra of a two-dimensional valence hole gas we identify the three-level energy spectrum of a free positive trion with a field-induced singlet-triplet transition. The recombination spectrum of acceptor-bound trions is also detected, including a cyclotron replica corresponding to the hole shake-up process. The emergence of a shake-up peak at low temperature is shown to be a sensitive probe of the presence of a small number of impurities inside the high-mobility quantum well, and its relative position is directly related to the hole cyclotron mass.

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Quantization of single-particle energy into macroscopically degenerate, widely separated Landau levels (LLs) makes the two-dimensional (2D) gas of charge carriers in a strong magnetic field a unique setting for studying the non-perturbative many-body interaction phenomena. Eminent examples of discoveries made in these systems include fractional quantum Hall effect [1], emergence of incompressible fluids with fractional or nonabelian quasiparticles [2, 3, 4], or formation of topological "skyrmion" excitations [5, 6] carrying massive spin per unit charge.

A powerful tool used to study interacting 2D carriers is photoluminescence (PL) spectroscopy [7, 8]. In a PL experiment, additional electron–hole (e–h) pairs are introduced into the system through photon absorption, and response of the surrounding carriers makes the recombination spectrum sensitive to their many-body dynamics.

Since their prediction [9, 10] and successful experimental detection [11], trions ($X^{\pm} = 2e + h$ or $2h + e$) have been recognized to play a crucial role in the PL spectra of 2D gases [12, 13, 14]. The three-body dynamics of a trion might at first sight seem analogous to the familiar Hydrogen ion problem. However, comparable e and h masses, confinement, magnetic field, nonparabolic and anisotropic hole dispersion, and coupling to the crystal lattice, surrounding carriers, or impurities – all generate complexity making trions fascinating objects of intense experimental [15, 16, 17, 18, 19, 20] and theoretical [21, 22, 23, 24, 25, 26, 27, 28] research.

Nonetheless, the role of trions or other e–h complexes in magneto-optical spectra is still far from being completely understood. Especially the hole gas remains relatively less thoroughly explored because of both more complicated valence band structure and a larger difficulty in achieving ultra-high carrier mobility. The last point invokes the puzzling question of the role played by localization or, alternatively, of the influence of weak disorder

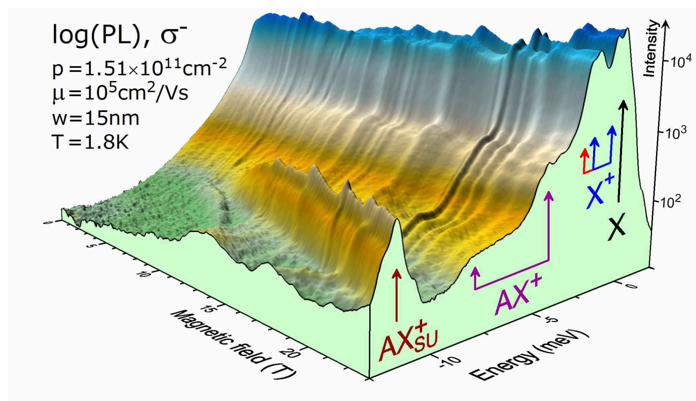

FIG. 1: (color online) The σ^- polarized PL spectrum of the 2D valence hole gas as a function of the magnetic field. Energy is measured from the exciton line. Arrows mark several peaks identified at high fields: exciton X, trions X^+ (red for spin-singlet and blue for two triplets), and emission spectrum of the acceptor-bound trion AX^+, including a shake-up line AX^+_{SU}.

in strongly interacting 2D systems of carriers.

This very question is addressed in the present paper. We report magneto-optical studies of a high-quality 2D hole gas in a GaAs quantum well. By precise control of experimental conditions we were able to record very rich spectra shown in Fig. 1, including free excitons and positive trions, and the transitions involving trions bound to residual neutral acceptors inside the well. In the free trion spectrum, all three anticipated [25] bound states have been identified. Of those, the positive "dark triplet" state X^+_{td} has not, to our knowledge, been previously observed. Crossover to the X^+_{td} ground state has been found at the magnetic field $B \approx 12$ T. The variation of energy and intensity of the free trion peaks appears in coincidence with expected formation of the incompressible hole fluids. The spectrum of impurity-bound trions con-

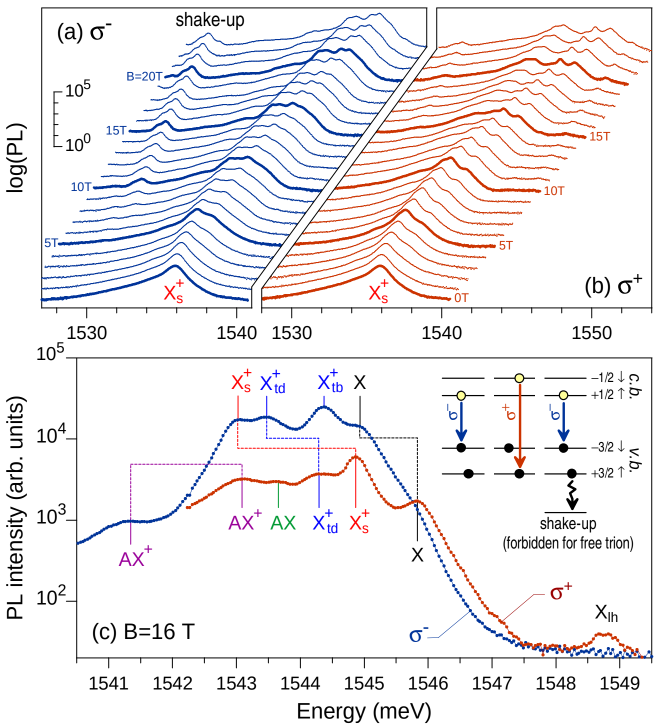

FIG. 2: (color online) Top: Comparison of (a) σ^- and (b) σ^+ polarized PL spectra at a sequence of magnetic fields between $B = 0$ and 23 T (same sample as in Fig. 1). Bottom: Magnified spectra at $B = 16$ T. Several identified lines include free exciton X and three positive trions X^+ (spin-singlet and two spin-triplets), acceptor-bound exciton AX and trion AX^+, and a light-hole exciton $X_{\rm lh}$. Note different spin splittings of the X, AX^+, and different X^+ states. Inset: Schematic of the $\sigma^\pm$ polarized transitions of a positive spin-singlet trion.

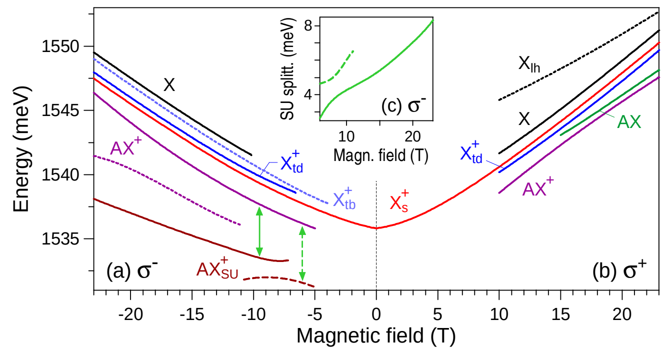

FIG. 3: (color online) Magnetic field dependence of recombination energies identified in polarizations σ^- (a) and σ^+ (b) in the PL spectra in Fig. 2. (c) Splitting of the shake-up line.

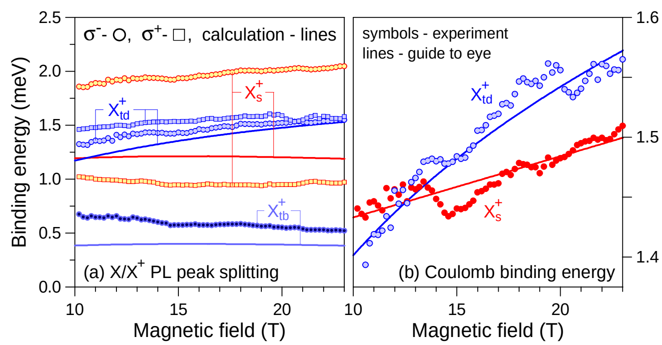

FIG. 4: (color online) (a) Magnetic field dependence of the trion binding energies determined from the exciton–trion peak splittings, $\Delta = E[X] - E[X^+]$; lines – numerical calculation. (b) Coulomb binding energies of the singlet and dark triplet trions, obtained as $\sigma^\pm$ averages $\frac{1}{2}(\Delta^+ + \Delta^-)$ to remove Zeeman effect. The crossover occurs at $B \approx 12$ T, and adding the hole Zeeman term to $E[X_{\rm s}^+]$ shifts it to an even lower field.

stitutes a sensitive probe of the weak disorder in our sample. It contains a cyclotron replica corresponding to the "shake-up" process [29, 30, 31] in the valence band. Identification of all transitions and especially establishing the role of acceptors located inside the well was achieved by comparison of experimental data with realistic numerical calculations. Led by prediction that the shake-up splitting is a bare cyclotron energy, we were also able to determine the hole cyclotron mass and observe an anticrossing of the heavy- and light-hole subbands at $B \approx 8$ T.

The studied sample was a GaAs/Al$_{0.35}$Ga$_{0.65}$As quantum well of width $w = 15$ nm, grown by molecular beam epitaxy on a (001) semi-insulating GaAs substrate and symmetrically δ C-doped in the barrier on both sides. The concentration and mobility of the holes measured at low temperature ($T = 4.2$ K) were $p = 1.51 \cdot 10^{11}$ cm^{-2} and $\mu = 1.01 \cdot 10^6$ cm^2/Vs (the latter corresponding to the hole mean free path comparable with electron systems at $\mu_e \sim 10^6$ cm^2/Vs). The PL was excited by a 720 nm red line of Titanium Sapphire tunable laser (below the energy gap in the barrier), and an additional 514 nm green ion Argon line (exceeding the gap) was used to decrease hole concentration. The spectra were recorded at $T = 1.8$ K and in high magnetic fields up to $B = 23$ T with a small step $\Delta B = 0.1$ T. We used Faraday configuration with the linear polarizer and wave quater placed together with the sample in liquid helium. To switch between the σ^- and σ^+ circular polarizations, the magnetic field direction was reversed.

The field evolution of the PL spectrum is presented in Fig. 2(a) and (b). In the absence of a magnetic field a single line is observed, with a characteristic exponential low-energy tail. It is due to recombination of a spin-singlet trion $X_{\rm s}^+$ (the only bound $2h+e$ state at $B=0$). More transitions appear when the magnetic field is applied. Also, a difference emerges between the two polarizations of emitted light, corresponding to the recombination of e–h pairs with different spins (↑-↓ for σ^- and ↓-↑ for σ^+). This is sketched in the inset in Fig. 2(c), showing the spectra for $B = 16$ T. The field dependence of all resolved transition energies is displayed in Fig. 3.

Among other peaks we identify a neutral exciton X and a pair of triplet trions: "dark" $X_{\rm td}^+$ and "bright" $X_{\rm tb}^+$

(the latter only visible in the stronger σ^- polarization). The exciton–trion peak splittings Δ are plotted as a function of B in Fig. 4(a). Especially for the X_s^+, difference between the exciton and trion Zeeman splittings must be taken into account to make comparison with the numerical Coulomb binding energies drawn with the lines [18, 19, 20]. This is done in Fig. 4(b) by averaging Δ over both polarizations, markedly improving agreement with the numerics. The singlet–triplet crossover ("hidden" in the PL spectra) is revealed at $B \approx 12$ T. The actual ground state transition occurs at a slightly weaker field due to the hole Zeeman term weakening the X_s^+ binding. This prediction matches the observed gradual decrease of the X_s^+ emission beyond $B \approx 10$ T.

Convincing identification of the weak lines found on the low-energy wing of the trion spectra was achieved by the comparison with realistic calculations. In the high-field σ^+ spectra, the AX state (an exciton bound to a residual neutral acceptor $A = A^- + h$ inside the quantum well) is identified. It is easily distinguished from charged complexes by additional application of a green laser which, at sufficient power density, converts the structure from p- to n-type (appropriate green illumination also enables detection of the excitonic peak down to $B = 0$). The pair of $\sigma^\pm$ lines labeled as AX^+ are attributed to the recombination of a trion bound to a neutral acceptor. At an even lower energy, a cyclotron replica of the AX^+ peak was detected. It describes a shake-up process [29, 30] in which the e–h annihilation is accompanied by excitation of a left-over acceptor-bound hole to a higher LL.

Remarkably, the selection rules associated with translational symmetry of the quantum well preclude shake-up recombination of free trions [31]. Furthermore, we found that shake-up which arises from scattering of trions by free carriers is virtually negligible at fractional LL fillings due to Laughlin trion–carrier correlations [27]. Also in the comparable electron systems shake-up is much weaker due to a larger cyclotron gap. These facts make our system well suitable for studying the shake-up effect. More importantly, its detection is a sensitive probe of a small number of residual impurities in a high-quality structure.

Calculation consisted of exact diagonalization of model hamiltonians of small e–h systems, with and without an additional point charge A^- in the middle of the quantum well (other near-center positions gave equivalent results, but placing A^- closer to the well's edge caused qualitatively different behavior which could not explain the experimental spectra). Two spin states and up to five LLs and two subbands were included for electrons and holes. Coulomb matrix elements were integrated exactly, using realistic 3D subband wave functions. Further details were recently given in Ref. [28] and will not be repeated here.

Let us summarize the numerical results. First, the Coulomb binding energy of 2.65 meV was obtained (including five LLs and two well subbands) for the neutral $AX = A^- + 2h + e$ state at $B = 15$ T. Assumming

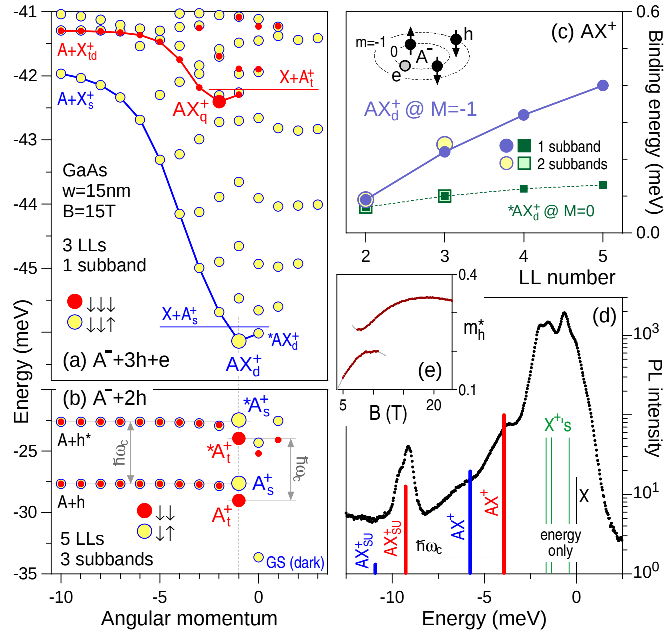

FIG. 5: (color online) Calculated energy spectra of (a) $3h + e$ and (b) $2h$ systems in the presence of an ionized acceptor A^- in the middle of a symmetric quantum well. In (a), AX_d^+ at angular momentum $M = -1$ is the spin-doublet ground state of an A-bound trion. In (c), its binding energy is compared to the weakly bound $^*AX_d^+$ at $M = 0$ as a function of the number of included LLs and subbands. In (b), four lowest final states for the $AX_d^+ \to A^+$ recombination are marked at $M = -1$. In (d), the corresponding four-peak AX_d^+ emission spectrum is overlaid with the experimental data of Fig. 2(a). In (e), the hole effective mass m_h^* is extracted from the splitting of the experimental shake-up line, equal to the hole cyclotron energy as predicted in (b). All data are for a 15 nm GaAs quantum well and, except for (e), for magnetic field $B = 15$ T.

the AX Zeeman splitting similar to X^+ and AX^+, this matches perfectly the observed relative position of AX in the PL spectrum. In the next step, a more strongly bound charged $AX^+ = A^- + 3h + e$ state was found in the presence of excess holes. It was established as the most stable radiative complex in the presence of an A^- (with the AX prevailing for the A^- located outside the well). An example of the $A^- + 3h + e$ spectrum is presented in Fig. 5(a). The ground state is a spin-unpolarized (doublet) state AX_d^+ with angular momentum $M = -1$ corresponding to the "compact" single-particle configuration shown in the inset in Fig. 5(c). The AX_d^+ has much lower energy than a trion unbound from the A (the A–X^+ interaction pseudopotential is drawn with a solid line). However, it is rather weakly bound against the break-up into a spin-singlet A_s^+ and a free exciton. Another marginally bound state $^*AX_d^+$ occurs at $M = 0$. All spin-polarized (quartet) states have higher energy, even with the Zeeman term, and thus can be neglected.

Fig. 5(c) compares the AX_d^+ and $^*AX_d^+$ binding energies Δ computed more accurately by including more LLs

or well subbands. Clearly, only the AX_d^+ is expected to show in PL, and its small $\Delta \sim 0.5$ meV makes the detection depend on low temperature (indeed, only the free X and X^+ are observed in our experiment above $T \sim 5$ K).

The accurate energy spectrum of A^+ (i.e., of the final state in the AX_d^+ recombination) is shown in Fig. 5(b). The four lowest A^+ states in the optically active $M = -1$ subspace (defined by the $\Delta M = 0$ selection rule) include two singlets and two doublets, derived from single-particle configurations with either both holes in the lowest LL (A^+) or with one hole in the higher LL ($^*\!A^+$).

The oscillator strengths for the $AX_\mathrm{d}^+ \to A_\mathrm{s}^+$, A_t^+, $^*\!A_\mathrm{s}^+$, and $^*\!A_\mathrm{t}^+$ transitions were calculated to predict the AX^+ recombination spectrum in Fig. 5(d). Coulomb transition energies obtained from exact diagonalization have been additionally shifted by the Zeeman correction determined from Fig. 2(c). Good agreement with the experimental PL spectrum supports identification of the AX^+ lines.

Remarkably, the energy distance between A_t^+ and $^*\!A_\mathrm{t}^+$ appears nearly identical to the hole cyclotron gap $\hbar\omega_c$ over a wide range of magnetic fields. This means equal binding between the neutral acceptor and a hole in the lowest or excited LL. More importantly, it allows extraction of the hole cyclotron mass m_h^* from the position of a shake-up line in the PL spectrum. The result for our experimental data shown in Fig. 5(e) reveals an anticrossing of the heavy- and light-hole subbands at $B \approx 8$ T.

In conclusion, using polarization-resolved magneto-PL of a 2D hole gas we detected all three states of a free positive trion (singlet, dark triplet, and bright triplet), earlier reported only for negative trions. The "hidden" singlet–triplet crossover is found at a rather weak field $B \approx 12$ T. We also observed correlation between the changes in energy and intensity of the trion recombination and condensation of the holes into a series of incompressible fluids, thus confirming high quality of the studied hole gas. Nevertheless, additional lower-energy PL lines could not be explained by assuming perfect translational symmetry. By combining experiment with analysis of optical selection rules and realistic numerics, we attributed these lines to the acceptor-bound trions, thus establishing PL as a sensitive probe of the weak disorder in our sample. A shake-up peak was also identified in the spectra, with the relative position unaffected by interactions and thereby directly linked to the hole cyclotron mass.

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